Baryon-Strangeness Correlations from Hadron/String- and Quark-Dynamics

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Abstract. Baryon-strangeness correlations (C_{BS}) are studied with a hadron/string transport approach (UrQMD) and a dynamical quark recombination model (quark molecular dynamics, qMD) for various energies from $E_{lab} = 4A$ GeV to $\sqrt{s_{NN}} = 200$ GeV. As expected, we find that the hadron/string dynamics shows correlations similar to a simple hadron gas. In case of the quark molecular dynamics, we find that initially the C_{BS} correlation is that of a weakly interacting QGP but changes in the process of hadronization also to the value for a hadron gas. Therefore, we conclude that the hadronization process itself makes the initial baryon strangeness correlation unobservable. To make an experimental study of this observable more feasible, we also investigate how a restriction to only charged kaons and Λ's (instead of all baryons and all strange particles) influences the theoretical result on C_{BS}. We find that a good approximation of the full result can be obtained in this limit in the present simulation.

A plasma of quarks and gluons is believed to be created in the course of the collision of two heavy nuclei travelling at ultra-relativistic speeds. Probes based on fluctuations have been proposed throughout the last decade to study the properties of QCD-matter close to the phase transition from hadronic to quark degrees of freedom [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Even though they promised to be most adequate due to the strongly fluctuating energy density, initial temperature, isospin or particles density no experimental data up to now relying on event-by-event analyses could show a decisive signal for the production of quark-gluon matter (QGP).

A novel event-by-event observable has been introduced by Koch et al. [11], the baryon-strangeness correlation coefficient C_{BS}. This correlation is proposed as a tool to specify the nature (ideal QGP or strongly coupled QGP or hadronic matter) of the highly compressed and heated matter created in heavy ions collisions. The idea is that depending on the phase the system is in, the relation between baryon number and strangeness will be different: On the one hand, if one considers an ideal plasma of quarks and gluons, strangeness will be carried by freely moving strange and anti-strange quarks, carrying baryon number in strict proportions. This leads to a strong correlation between baryon number and strangeness. On the other hand, if the degrees of freedom are of hadronic nature, this correlation is different, because it is possible to carry strangeness without baryon number, e.g. in mesons or QGP bound states.

To quantify to which degree strangeness and baryon number are correlated, the following correlation coefficient has been proposed [11]:

$$C_{BS} = -3\frac{\langle BS \rangle - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2} \quad , \tag{1}$$

where B is the baryon charge and S is the strangeness in a given event. If a QGP is created, the value of C_{BS} will be unity as expected from lattice QCD, compatible with the ideal weakly coupled QGP. For a hadron gas, where the correlation is non trivial, this quantity has been evaluated in [11] to be $C_{BS} = 0.66$.

In this paper, we study the correlation coefficient C_{BS} with the Ultra-relativistic Quantum Molecular Dynamics model (UrQMD v2.2) and the quark Molecular Dynamics model (qMD). The UrQMD is a non-equilibrium microscopic transport model that simulates the full space-time evolution of heavy ions collisions. It is valid from a few hundreds of MeV to several TeV per nucleon in the laboratory frame. It describes the rescattering of incoming and produced particles, the excitation and fragmentation of color strings and the formation and decay of resonances. This model has been used before to study event-by-event fluctuations rather successfully [3, 12, 13, 14, 15, 16] and yields a reasonable description of inclusive particle distributions. For a complete review of the model, the reader is referred to [17, 18]. Since the UrQMD is based on hadrons and strings it provides an estimate of the C_{BS} value in the case where no QGP is created, however taking into account the rescattering and the non-equilibrium nature of the heavy ion reactions.

In contrast, the qMD model provides an out-of-equilibrium estimate of C_{BS} with an explicit phase transition from QGP to hadronic matter. It describes the dynamics and the hadronization through an effective heavy quark potential in which the quarks propagate with a final dynamical recombination to white clusters. These clusters are then mapped to known hadrons and resonances that are later allowed to decay. Note that qMD is a recombination model that does not violate energy and momentum conservation and does not reduce the entropy in the hadronization process. The reader is referred to [19, 20] for more details about the qMD model.

C_{BS} is evaluated from the event-by-event fluctuation analyses following [11]:

$$C_{BS} = -3\frac{\frac{1}{N}\sum_n B^{(n)}S^{(n)} - (\frac{1}{N}\sum_n B^{(n)})(\frac{1}{N}\sum_n S^{(n)})}{\frac{1}{N}\sum_n (S^{(n)})^2 - (\frac{1}{N}\sum_n S^{(n)})^2} \tag{2}$$

$B^{(n)}$ and $S^{(n)}$ stand for the baryon number and strangeness in a given event n.

If a QGP is created, the signal given by the C_{BS} coefficient should survive the hadronic phase only if the flow is strong enough. I.e. strangeness and baryon number within a given rapidity range should be frozen in. The rapidity window used must not be too wide in order to avoid global baryon number and strangeness conservation which will lead to a vanishing correlation. Nevertheless, the acceptance window must be wide enough to avoid smearing due to hadronization. A suggested reasonable width is of the order of $y_{max} = 0.25 - 0.5$.

The energy scan of C_{BS} for central Au+Au/Pb+Pb collisions as calculated with UrQMD is shown as full circles in Figure 1. As discussed in [11], C_{BS} increases with an increase of the baryon chemical potential μ_B, i.e. when going to lower beam energies. With increasing collision energy, and therefore decreasing μ_B, C_{BS} goes down to
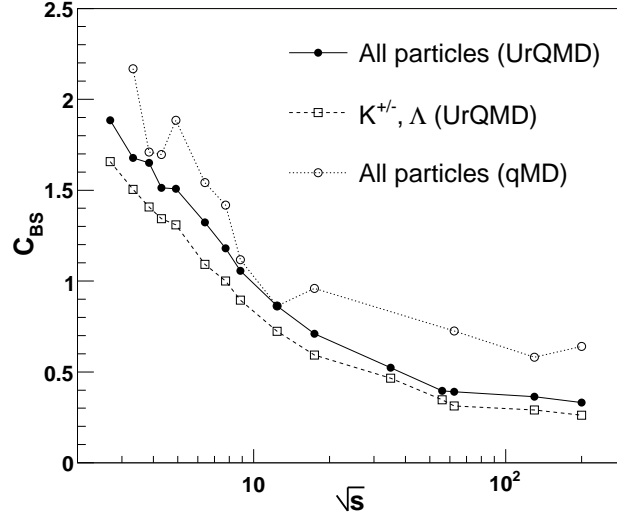
FIGURE 1. Correlation coefficient C_{BS} for central Au+Au/Pb+Pb as a function of $\sqrt{s}$ calculated with UrQMD with all particles taken into account (full circles) and only Λ's and charged kaons (open squares). Open circles are calculated with the qMD model using all particles. The rapidity window is $y_{\max} = 0.25$.

$C_{BS} \approx 0.4$ at the highest RHIC energy available and is slightly lower than the value for a fully thermalized hadron gas. Unfortunately it is difficult to explore C_{BS} directly in experiment, because it includes contributions from neutrons and other difficult to measure hadrons. It is therefore desirable to test, if also a better accessible subset of particles can be used to explore this correlation. Therefore, we study next, how C_{BS} is modified if only charged kaons and Λ's are taken into account. As shown in Fig. 1 (open squares) one observes that this subset of particles leads in good approximation to the same results for C_{BS} at high energies as for the full set of hadrons. Therefore, we conclude that a measurement of the energy dependence of the C_{BS} correlation extracted out of charged kaons and Λ's only might be sufficient to measure the correlation between baryon number and strangeness in heavy-ions collisions.

Let us finally discuss how a model with quark degrees of freedom compares to the hadron/string dynamics results. As shown in Fig. 1 (open circles) the result from the quark molecular dynamics model follows roughly the shape of the UrQMD values. Especially towards the highest RHIC energy C_{BS} decreases below the QGP expectation of $C_{BS} = 1$. This surprising result strongly contrasts with the expected value for an ideal quark-gluon-plasma and might be a first indication that smearing due to hadronization process itself might have drastic effects on fluctuation observables.

Let us explore this important question further by studying the time evolution of C_{BS} within the qMD for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as shown in Fig. 2. At early times one observes that $C_{BS} \approx 1$, in agreement with the expectations for a quark-gluon-plasma. However, around 6 fm/c (when the hadronization starts) C_{BS} decreases strongly and reaches its final value $C_{BS} \approx 0.6 - 0.7$. One should note that there is no hadronic rescattering stage in qMD, thus, the decrease of the correlation is solely related to the
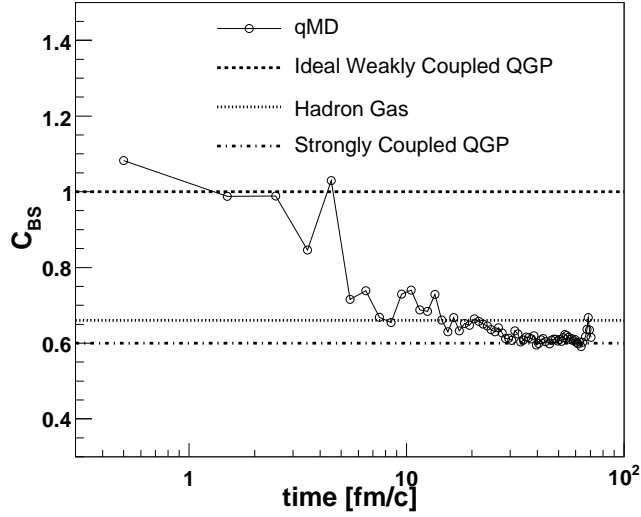
FIGURE 2. Correlation coefficient from the quark molecular dynamics calculation for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of time at midrapidity. The maximum rapidity accepted is $y_{max} = 0.25$. Also shown here are the values for an ideal weakly coupled QGP, a strongly coupled QGP and for a hadron gas.

recombination-like hadronization process in the model. Thus, the present investigation might explain why no signal of the phase transition has been observed in the data up to now. Because even if the initial state consists of a quark-gluon-plasma with the expected fluctuations, these fluctuations might be completely blurred in the hadronization process.

To summarize, we have studied the dependence of the baryon-strangeness correlation coefficient as a function of energy from $E_{lab} = 4A$ GeV to $\sqrt{s_{NN}} = 200$ GeV for central Au+Au/Pb+Pb reactions with two different models. The UrQMD model is based on string-hadronic degrees of freedom, whereas the qMD model contains an explicit quark phase and a transition from quark to hadronic matter. C_{BS} is found to decrease from the lower energies towards the top RHIC energy in both approaches. At the highest RHIC energy the C_{BS} value from the hadron/string transport model is roughly half the one expected in the case of a QGP. However, the calculation including a phase transition gives similar results as without phase transition, in clear contradiction with what has been expected in case a plasma of quarks and gluons as the initial matter. This finding is traced back to the hadronization process itself that destroys the initially present correlations.

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